THE PHELIX LINER DEMONSTRATION EXPERIMENT (PLD-1)

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Abstract

The PHELIX Liner Demonstration Experiment (PLD-1) took place in September of 2010 at Los Alamos National Laboratory. The PHELIX machine consists of a ~500 kJ single-marx capacitor bank cable-coupled to a toroidal 1:4 current step-up transformer which delivers multi-Mega-Ampere currents to a cm size load. In this experiment the load consisted of a ~3 cm radius, 0.8 mm thick, ~3 cm tall aluminum liner, copper glide planes, a thin polyethylene insulator, and a 0.5 cm thick aluminum return conductor. Two independent channels of fiber optic Faraday rotation measured a peak load current > 4 MA with a pulse width of ~ 10 µs. Four linear Rogowski coils measured the output current of the 4 marx modules. High-resolution flash X-radiography imaged a stable, highly symmetric and uniform liner 14.5 µs after current start. A 12 channel laser Doppler velocimetry (LDV) system tracked the inside surface of the liner throughout the experiment and showed a peak velocity before impact with probes of ~ 1 km/s. The LDV probes were arrayed axially as well as azimuthally and confirmed the symmetry of the liner trajectory. Surprisingly, the LDV showed distribution of velocities of the inner liner surface late in time. PLD-1 is the first step towards utilizing the PHELIX pulsed-power system at the Los Alamos proton radiography facility.

I. INTRODUCTION

The PHELIX machine design must be compact and efficient to be effectively used in the Los Alamos proton radiography “pRad” facility. This facility permits up to 20 frames of pictures with an 800 MeV proton beam with sub-millimeter scale resolution. The PHELIX machine can also include multi-axis flash x-ray radiography. The pulsed power system consists of 4 air insulated marx modules, paired into a small “two-stack” assembly as shown in Figure 1. The system is low inductance with multiple and couples very efficiently to a toroidal multi-filar air core transformer as shown in Figure 2. The transformer is connected to the marx modules with (multiple) short lengths of coaxial cable that also become the multi-filar transformer primary windings in a single length with no interconnections. Each marx has 10 output cables. The conceptual design of PHELIX transformer is shown in Figure 3 and demonstrates a magnetic coupling coefficient of ~ 94%.

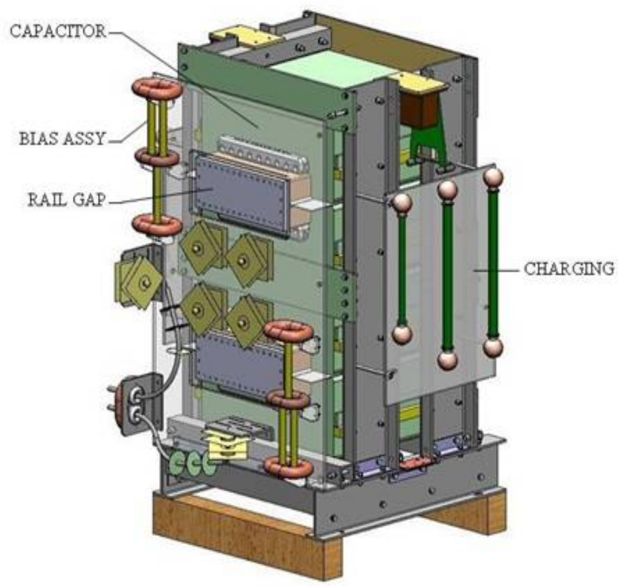

Figure 1. 120 kV, 240 kJ, "two-stack" air insulated marx modules.

Figure 2. Torodial multi-filar air core transformer with dynamic load cassette assembly and diagnostics.

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14. ABSTRACT
The PHELIX Liner Demonstration Experiment (PLD-1) took place in September of 2010 at Los Alamos National Laboratory. The PHELIX machine consists of a ~500 kJ single-marx capacitor bank cable-coupled to a toroidal 1:4 current step-up transformer which delivers multi-Mega- Ampere currents to a cm size load. In this experiment the load consisted of a ~3 cm radius, 0.8 mm thick, ~3 cm tall aluminum liner, copper glide planes, a thin polyethylene insulator, and a 0.5 cm thick aluminum return conductor. Two independent channels of fiber optic Faraday rotation measured a peak load current > 4 MA with a pulse width of ~ 10 ìs. Four linear Rogowski coils measured the output current of the 4 marx modules. High-resolution flash X-radiography imaged a stable, highly symmetric and uniform liner 14.5 ìs after current start. A 12 channel laser Doppler velocimetry (LDV) system tracked the inside surface of the liner throughout the experiment and showed a peak velocity before impact with probes of ~ 1 km/s. The LDV probes were arrayed axially as well as azimuthally and confirmed the symmetry of the liner trajectory. Surprisingly, the LDV showed distribution of velocities of the inner liner surface late in time. PLD-1 is the first step towards utilizing the PHELIX pulsed-power system at the Los Alamos proton radiography facility.

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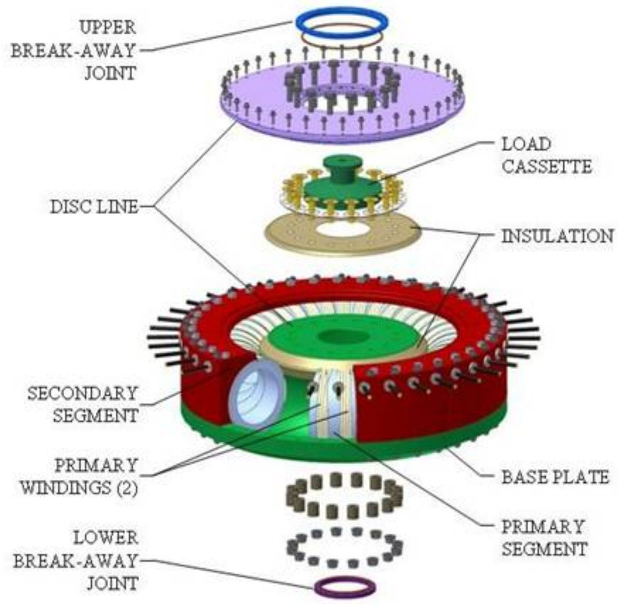

Figure 3. PHELIX air core transformer and integral load assembly.

To achieve the high coupling coefficient and a low uncoupled inductance, the transformer secondary encases the multi-filar primary windings and then becomes an integral part of the transmission disc line which directly connects to the load cassette assembly. The transformer is reusable and only requires the change of the load cassette assembly between shots. To further maintain an excellent inductance budget, conformal and stretchable insulation, required of all three dimensions, is used in the disc line assembly. This compact system assembly provides over 5 Megamperes current when short circuit tested with ~240 kJ energy as shown in Figure 4. This result is notable and provides ~ 20 MA per megajoule of stored energy. The results were obtained by incrementally increasing the charge voltage and after a series of 16 tests we were in the appropriate regime (+/- 42 kV) where we could initiate the hydrodynamic tests.

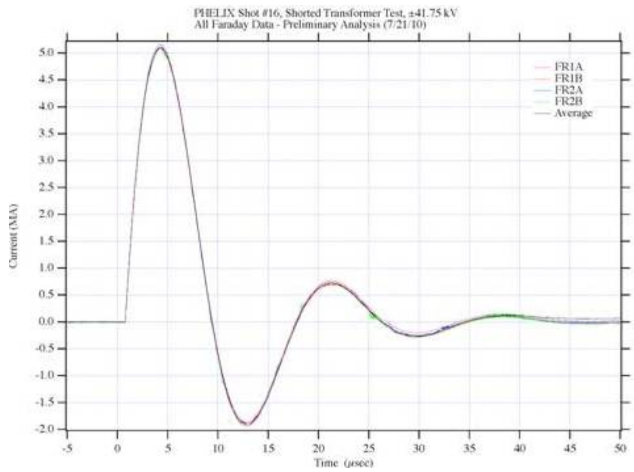

Figure 4. 5 MA test shot at ~42 kV and ~240 kJ.

II. PLD-1 SHOT TEST RESULTS

A. Faraday Rotation

For PHELIX Liner Dynamic shot 1, PLD-1, two independent measurements of the current flowing from the transformer to the load are made using two fiber-optic loops that are embedded in a channel in the top disc line component of the load assembly. The change in the current enclosed by the loops is determined by measuring the change in the magnetic field integrated along the fiber-optic loop by detecting the Faraday rotation of linearly polarized light traveling through the fiber. The amount of polarization rotation of the light is related to the integrated magnetic field and therefore the enclosed current (Ampere's law) through the Verdet constant which for the optical-fibers used in this experiment has been determined to within 1%. The secondary current of 4.11 MA as measured by the fiber-optic Faraday rotation systems is shown in Figure 5.

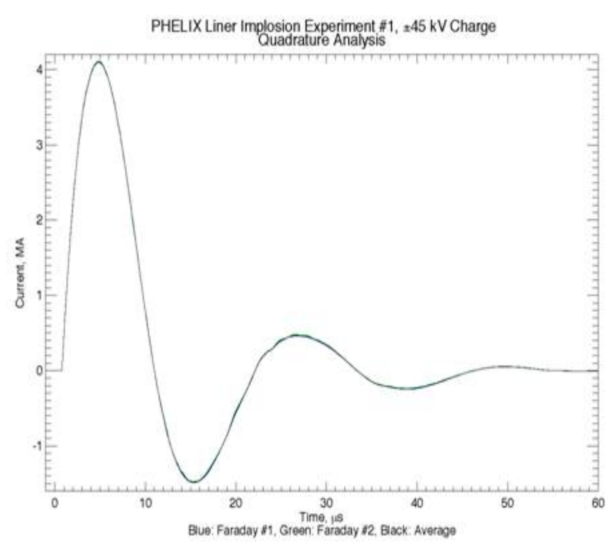

Figure 5. Faraday rotation diagnostic with 4.1 MA liner implosion current.

B. Liner Motion

The velocity of the liner's inner surface is measured using laser Doppler velocimetry (aka LDV). For PLD-1, the liner velocity was measured at 12 points on the interior of the liner. Eight points where azimuthally distributed on the horizontal mid-plan of the liner with an angular spacing of 45°. Two points were located on a plane 10 mm above the mid-plane, and two points were located on a plane 10 mm below the mid-plane. Figure 6 shows a diagram of the laser Doppler velocimetry probe holder and a map of the probe locations. All 12 points returned data for the duration of the PLD-1 experiment. A velocity spectrogram from the LDV diagnostics is shown in Figure 7 and Figure 8. Figure 9 shows the liner displacement for each point as determined by integrating the measured velocity.

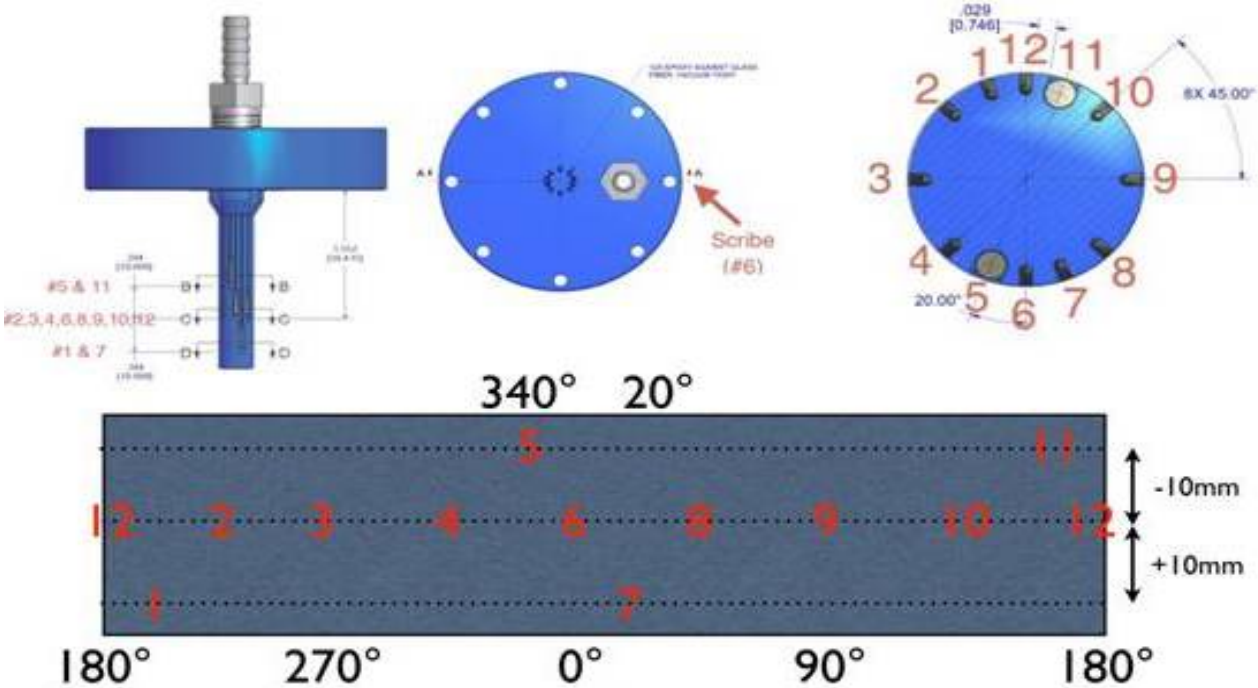

Figure 6. Sketch of laser doppler velocimetry probe an map of location of velocity measurements along inside surface of liner.

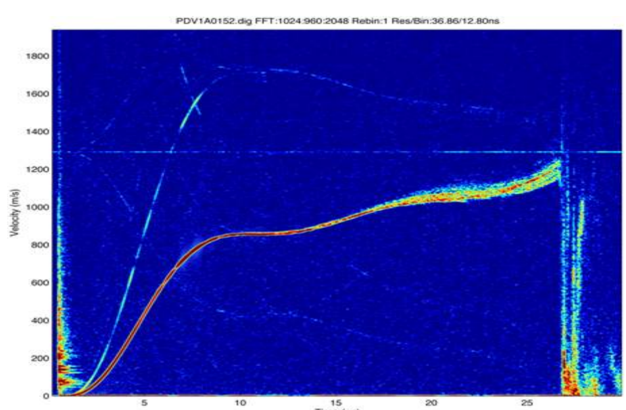

Figure 7. PLD-1 laser doppler velocimetry spectrum for probe #1.

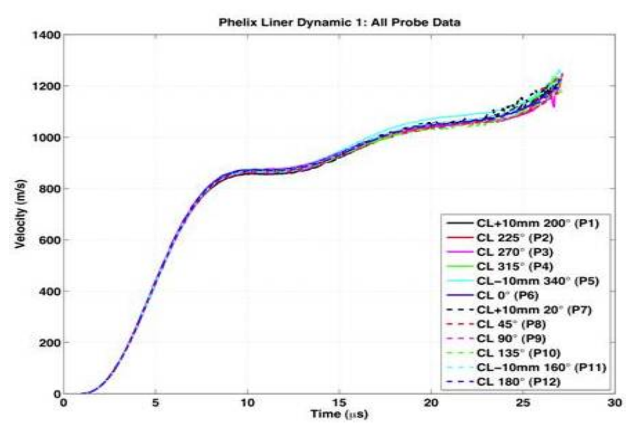

Figure 8. Velocity measured by the 12 laser doppler velocimetry points on PLD-1.

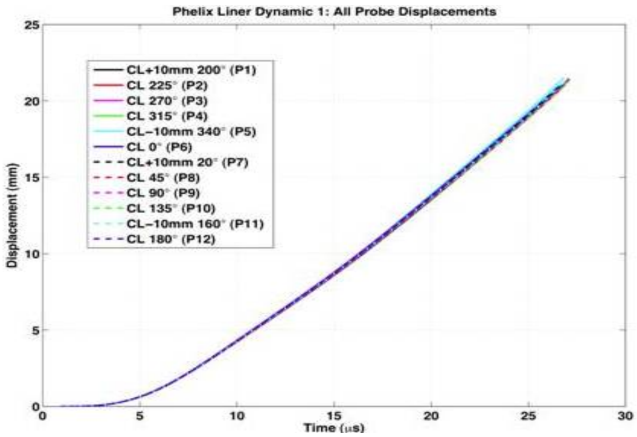

Figure 9. Liner displacements determined by integrating velocity measured by the 12 laser doppler velocimetry points on PLD-1.

C. Flash X-Radiography

Flash X-radiography is used in PLD-1 to image the location and condition of the liner and the return current conductor at a point in time during the implosion. Radiographs are taken before the experiment (static) and at 14.5 μs after current start (dynamic) and after completion of the experiment (post-shot). The static, dynamic and post-shot radiographs are shown in Figure 10. In the dynamic radiograph, the liner appears uniform showing a limited amount of interaction with the glide plane. Also, the return current conductor shows outward displacement in the dynamic radiograph and its final resting location in the post-shot radiograph.

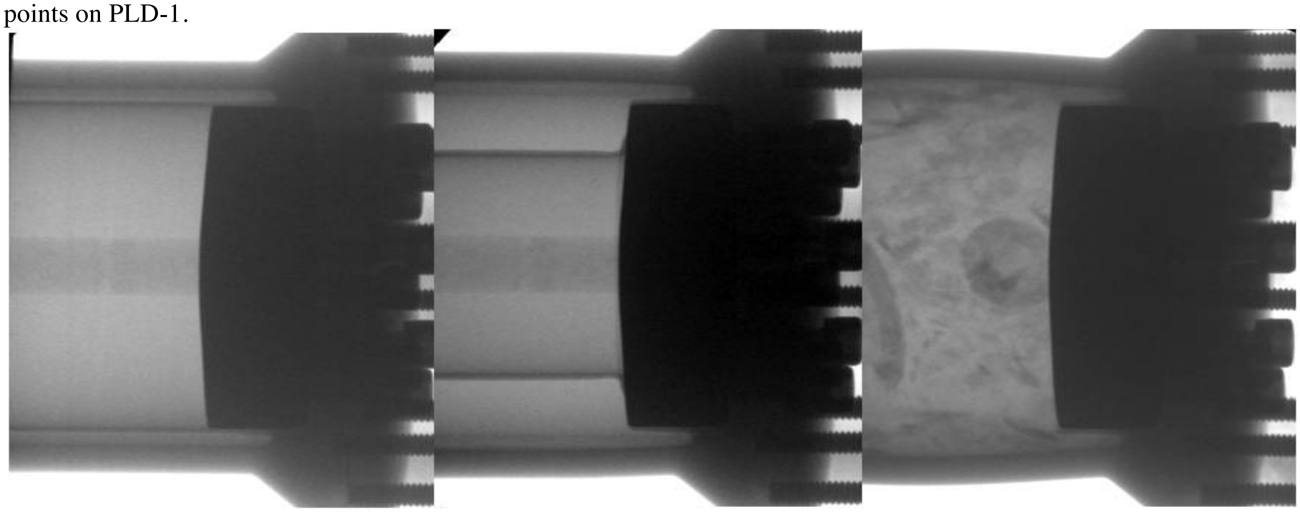

Figure 10. Static, dynamic, and post-shot X-radiographs (left to right) of PLD-1 showing the return current conductor, insulator, liner, velocimetry probe holder and one of two glide-planes. The dynamic radiograph indicates that at the time of the radiograph the liner is imploding uniformly with limited interaction with the glide-plane.

D. Primary side I-dot

For PLD-1, LANL made linear Rogowski sensors are used to measure I-dot, *M dI/dt*, from each of the capacitor pairs. *M* is the mutual inductance between the primary cables and the Rogowski sensors. The results are shown Figure 11. Given that for PLD-1 we are using linear Rogowski sensors, not closed coils, differences in the mutual inductance between the sensor and the bank for each channel can result in differences in the signal measured. Other sources of differences include variations in the capacitance and resistance of the capacitor pairs.

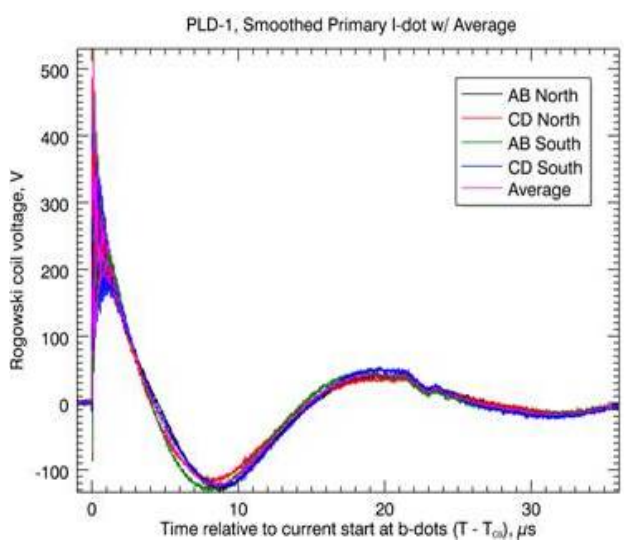

Figure 11. Signals from the 4 rogowski sensors on the PHELIX capacitor bank, one for each capacitor pair, along the average of the four.

E. Primary side I

In addition to measuring the direct signals from the Rogowski coils, the signals are integrated using passive RC integrators and then digitized. The signal are integrated at the input of the digitizing scope using integrators with a time constant, RC, of approximately 930 μs, such that we are measuring.

$$V = \frac{1}{RC}\int M\left(\frac{dI}{dt}\right)dt$$
$$= \frac{1}{RC}MI.$$

Figure 12 shows the RC integrated Rogowski data.

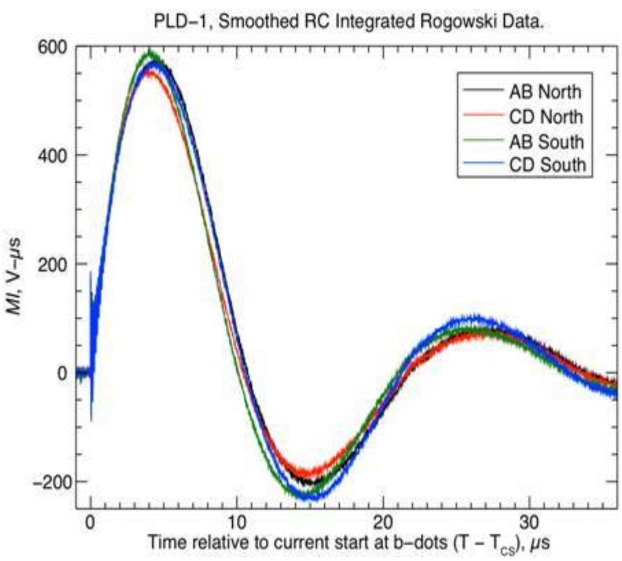

Figure 12. RC integrated rogowski signals.

F. Secondary Side dB/dt (B-dot)

Four B-dot probes separated azimuthally by 90° are located in a groove in the target cassette such that they measure the change in the magnetic field as a result of the current flow. The B-dots are used to detect the start of current flow during the experiment. The results of PLD-1 are show in Figure 13.

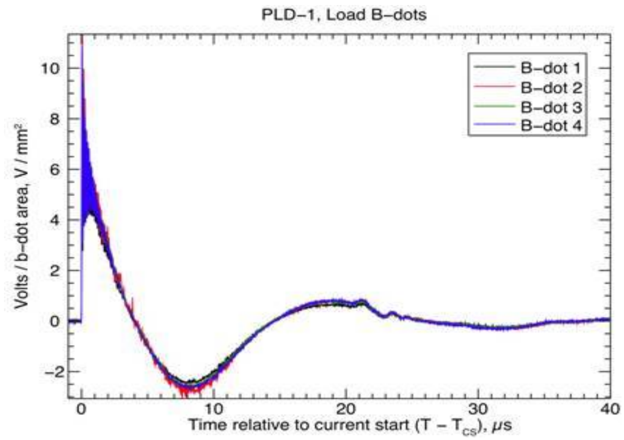

Figure 13. PLD-1 B-dot data.

III. COMPARISON TO CALCULATIONS

1D MHD simulations of the PLD-1 experiments have been made and are shown in Figure 14. This shows a summary of the output of one calculation and compares it to the data. They show good agreement with 2 caveats. First, an additional 2 nH of uncoupled inductance needs to be added to the circuit model in order to match the load current. Secondly, 50 microns thickness needs to be removed from the liner to match the PDV data. Presently investigations are being made to physically account for the discrepancy between the data and the calculations.

IV. SUMMARY

The PHELIX project met its portion of the C-1 L2 milestone by completing the design and fabrication of the PHELIX pulsed power machine at TA-53, MPF-18. The PHELIX project has completed the required tests to characterize its performance. The tests included:

- Cable Short Test on 7 July 2010 in which the capacitor banks where characterized.
- Transformer Test on 21 July 2010 in which the combined capacitor bank and transformer system were operated with static short across the secondary winding of the transformer.
- Dynamic Liner Test (PLD-1) on 14 September 2010 in which a cm size liner was accelerated to ~1 km/s. It was diagnosed with both flash X-ray and multi-channel LDV. Other diagnostics included Faraday rotation for load current, b-dots for detection / timing of current flow, and Rogowski coils to measure the primary winding current.

Additionally, a computer model of the PHELIX system has evolved with each successive test. With PHELIX operation having been demonstrated and its performance characterized. The next step in the project is to integrate the PHELIX machine onto a transportable module such that it can integrate with the LANL proton radiography facility in "Area-C".

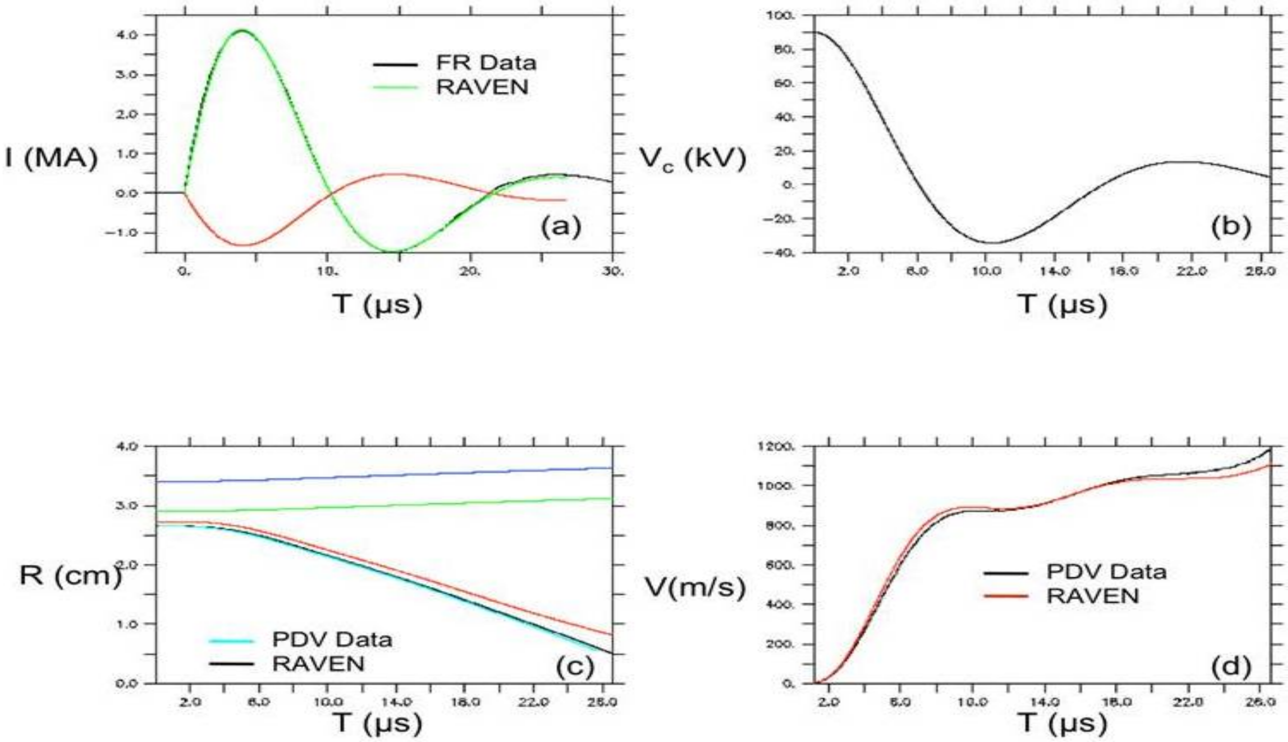

Figure 14. 1D MHD simulations of PLD-1. a)primary winding current (red) and secondary winding current (green) compared to data (black). b) The capacitor voltage. c) Trajectories of the liner (black and red) and return conductor with data (cyan). d) Velocity of the inner surface of the liner (red) compared to data (red).